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Underwater Implosions of Large Format Photo-multiplier Tubes

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Abstract

Large, deep, well shielded liquid detectors have become an important technology for the detection of neutrinos over a wide dynamic range of a few MeV to TeV. The critical component of this technology is the large format semi-hemispherical photo-multiplier tube with diameters in the range of 25 to 50 cm. The survival of an assembled array of these photo-multiplier tubes under high hydrostatic pressure is the subject of this study. These are the results from an R&D program which is intended to understand the modes of failure when a photo-multiplier tube implodes under hydrostatic pressure. Our tests include detailed measurements of the shock wave which results from the implosion of a photo-multiplier tube and a comparison of the test data to modern hydrodynamic simulation codes. Using these results we can extrapolate to other tube geometries and make recommendation on deployment of the photo-multiplier tubes in deep water detectors with a focus on risk mitigation from a tube implosion shock wave causing a chain reaction loss of multiple tubes.

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1. Introduction

The Long-Baseline Neutrino Experiment (LBNE) [1] has been proposed to study the fundamental properties of neutrinos, especially the mixing angle θ_{13} , mass ordering of the three known neutrinos and Charge Parity (CP) symmetry violation. Measurement of leptonic CP violation is important because it could connect to the dominance of matter over antimatter in the universe. A large (200 kton) well shielded water Cerenkov detector is one of the technologies under consideration for the far detector of LBNE [2].

The critical component of a large water Cerenkov detector is the large format semi-hemispherical photo-multiplier tube (PMT) with diameters in the range of 25 to 50 cm. Photomultiplier tubes are glass-enclosed vacuum tubes that are extremely sensitive to light. The typical glass used for the PMT bulbs is borosilicate glass which has about 70% SiO₂ and 20% B₂O₃, with rest made of metal oxides.

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The ability of the PMTs to withstand the water-column hydrostatic pressure at a maximum depth at ~ 0.8 MPa gauge pressure is crucial to the success of the experiment. When a PMT implodes due to hydrostatic pressure, the glass shatters and the water rushes inwards occupying the volume in a few milliseconds. At the end of this period the water velocity will come to an abrupt halt and the kinetic energy of the water will be transformed into a shock wave propagating outward. The resulting shock wave could impact nearby PMTs with sufficient force causing a cascade failure of neighboring PMTs. In order to better understand the characteristic of the shock wave and implosion phenomenon, we have performed two PMT implosion tests and compared the test data with a detailed computational model that includes the glass bulb geometry and material properties. This paper will focus on characterization of the implosion shock wave from a single bulb using data and simulations.

This is a reduced version of the article reporting our preliminary PMT implosion test results, the full version of the study is available at [3].

2. Experimental Setup

Two Hamamatsu R7081 PMTs were used for the tests. Prior to testing, these two PMTs were hydrostatically tested to 0.69 MPa at Brookhaven National Laboratory (BNL) to prevent unintentional PMT implosion during the test. The glass thicknesses of the PMTs were measured (using an ultrasonic gauge) at several diameters going around the central axis of the PMT. The PMT was rigidly secured to an aluminum plate at the equator of the tube. A hydraulic cylinder with a steel bolt plunger to induce bulb break was secured to the aluminum plate and aligned to an area of thin glass.

The test stand was installed at the Propulsion Noise Test System (PNTS) located at the Naval Underwater Warfare Center (NUWC) in Newport RI. PNTS has a spherical steel vessel which is 15.3 m in diameter, with a capacity of $1,893 \text{ m}^3$ of water. It can be pressurized, using an external pressure source, up to about 0.69 MPa at the center of the vessel. The PNTS has a grated work platform about 0.76 meter below the center line. The PMT in its test stand was installed at a 0.46 meter offset from the sphere center to reduce the adverse timing effect of the vessel wall reflected shock wave. The sensors were attached to a PVC piping frame. PVC pipe (with water inside) was used because it was considered to have the best impedance match with water so as not to disrupt the shock wave. Underwater lights and high speed cameras were mounted on the overhead I-beam of the platform. Figure 1 shows the PMT setup structure and the sensors around the PMT.

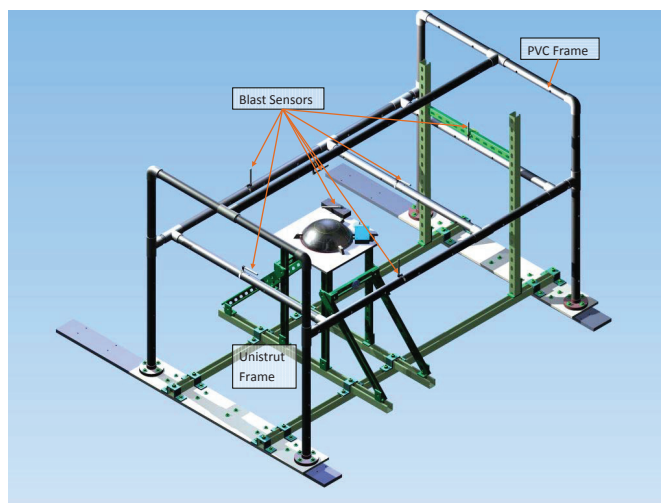


Fig. 1: Test stand with PMT and instrumentation installed

The dynamic pressure sensors were PCB Tourmaline Underwater Blast ICP Sensors (Model 138A01 and 138A02). Each sensor was connected using PCB Polyurethane Low Noise Coaxial Cable (Model 038), and once outside the pressure vessel, each cable was spliced to RG 6/U Quad Shield 18 AWG-type CATV or CMP coaxial cable which was connected to a PCB (Model 481A-050-080) Signal Conditioner. The outputs from the signal conditioner were routed to either a TEAC Integrated Recorder (Model GX-1, sample rate at 200 kHz/channel) or an IO Tech Wavebook (Model 516E, sample rate at 500 kHz/channel).

For our test the water was filtered during the filling process to reduce water contamination and provide the best possible clarity for the high speed camera recordings in the PNTS. The water temperature was about 13°C. With the PNTS filled to its capacity, the internal pressure of the vessel was increased at a rate of approximately 0.069 MPa/second using pressurized air. The PNTS was pressurized to 0.61 MPa at the center of the vessel.

Figure 2 shows a sequence of photographs from one of the high speed cameras (6006 frames per second) used in one PMT failure test. It clearly shows a “grid” of cracks that formed on the PMT followed by the nearly symmetric collapse and the in-rush of water and expulsion of glass after completion of implosion.

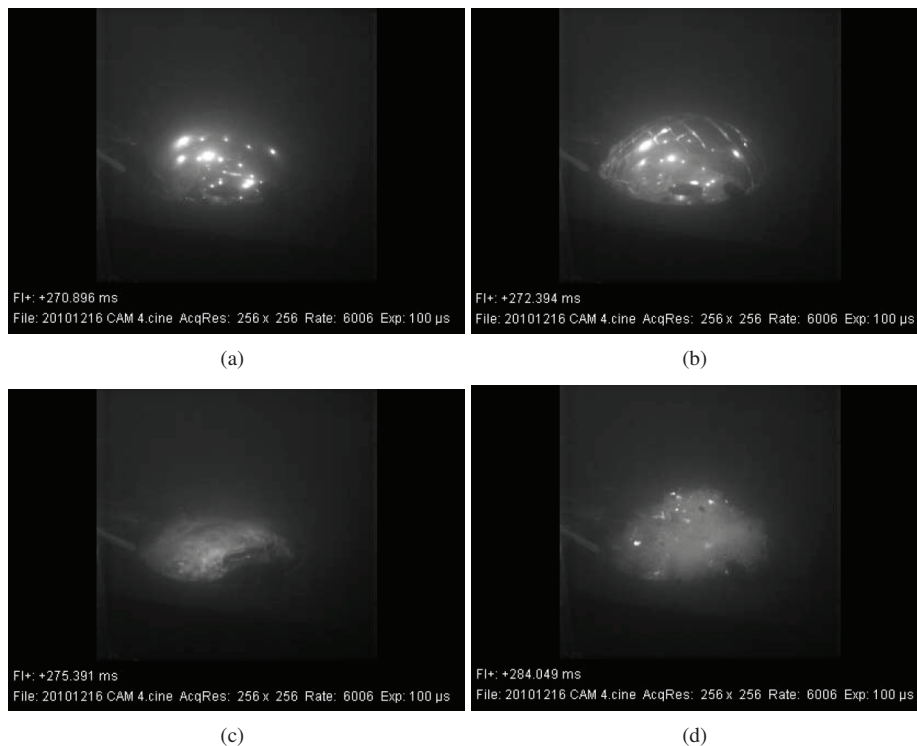


Fig. 2: The PMT implosion footage

3. Test Data Results

Seven PCB ICP blast sensors were located at different locations and distances from the imploded PMT to monitor the characteristics of the shock wave and its propagation. Six sensors were mounted on the PVC piping frame. The remaining one (ACC11) was mounted directly onto the PMT support plate to serve to mark the time of the implosion start. Each blast sensor was calibrated and the sensitivity was approximately 0.71 V/MPa over the measurement range of 0-6.9 MPa with the uncertainty of ± 0.09 MPa.

A plot of the pressure waveform data for one sensor (ACC5) is shown in Figure 3. At time “T0”, the sensor detected the hydraulic cylinder’s force as the glass started to crack. After about 1 ms and at time

“T1”, the PMT collapsed, high pressure water started to rush in and compressed the extremely low pressure gas (PMT is evacuated to 10^{-7} mbar) in the PMT. The sensor detected the sudden drop of the water pressure and the collapse-phase ended when the gas reached it’s minimum volume (closure). At that moment the velocity of the water became zero. The hydrostatic pressure used in these experiments caused the water to achieve a very high velocity during the collapse-phase. Upon closure of the gas volume, the rapid change in water momentum caused compression of the water, and then a radial pressure wave (“T2”). The pressure wave propagated toward the pressure vessel wall and then was reflected back from the vessel wall toward the center (“T3”).

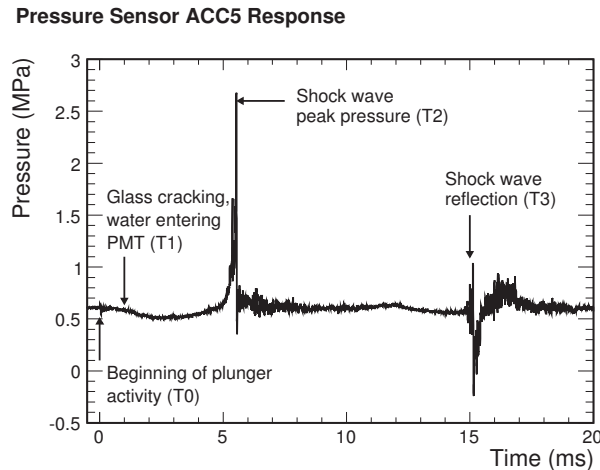


Fig. 3: The pressure waveform data of the PMT-1 implosion recorded by blast sensor ACC5

The pressure waveform data for sensor ACC1, ACC2, ACC3 and ACC4 are plotted in Figure 4 (a). During the collapse-phase (T2-T0), the pressure waveforms of sensors ACC1-4 are very similar. By multiplying the speed of sound in water at 13°C, we can convert the 0.04 ms peak pressure time difference between sensor ACC1 (or ACC2) and ACC3 (or ACC4) into a distance around 6 cm, which is about the radius of the PMT. This could imply that the center of the shock wave is not the same as the center of the PMT. We found it is useful to integrate the dynamic pressure with respect to time to calculate the impulse intensity, I , which is a measure of the momentum imparted to the water as the pressure wave passes through it [6]. Note that the dynamic pressure is obtained by subtracting the hydrostatic pressure from the absolute pressure, so that at $t=0$, the impulse intensity is zero. In Figure 4 (b), the impulse intensity is plotted as a function of time. For time, t , between 0 and 10 ms, the pressure data was integrated between 0 and t . The strength of the positive portion of the pressure pulse is the difference between the maximal impulse intensity (occurring at about 8 ms) and the minimal impulse intensity (occurring at about 4.7 ms). Although sensors ACC1, ACC2, ACC3 and ACC4 have the same distance from the PMT, they have quite different peak dynamic pressures (up to about 50%). However, they have very similar impulse intensities I (15%). This means that the momentum imparted to the water in the four directions is uniform, even though there is some local variation of the pressure waveform.

Several of the principal characteristics of the pressure pulses for seven blast sensors are listed in Table 1. One of the main characteristics of the pressure pulse is that all the seven sensors exhibit a very similar collapse pressure time duration (T2-T0), of about 5.6 ms, even though they are located at different distances from the center of the PMT. If we calculate the speed of the shock wave based on the relative differences of shock wave peak pressure time (T2) and distances (r) for different sensors, where r is the distance of the sensor from the PMT, the result is consistent with the speed of sound in water at 13°C. Another main characteristic of the pressure pulse is that the impulse intensities for these sensors show a clear $1/r$ relationship.

In order to check the repeatability of the test, another PMT (PMT-2) implosion test was conducted. The set-up remained the same as the first test. The result of the second PMT test is consistent with the first test.

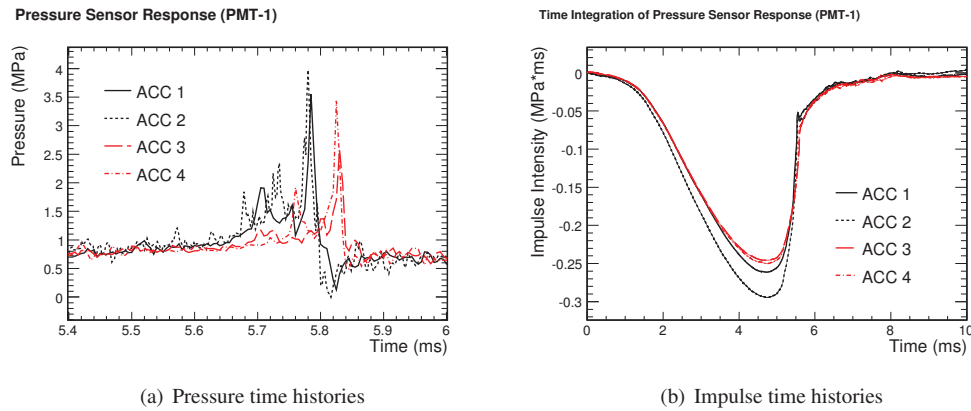


Fig. 4: The pressure and impulse intensity waveforms of PMT-1 implosion recorded by four blast sensors at the same distance from the PMT.

sensor	dist(mm)	T0(ms)	T2(ms)	T2-T0 (ms)	P_{peak} (MPa)	FWHM(ms)	I (MPa*ms)
ACC11	152	0.000	5.570	5.570	6.13	0.022	1.03
ACC5	482	0.260	5.800	5.540	2.68	0.018	0.26
ACC1	521	0.260	5.785	5.525	3.55	0.014	0.26
ACC2	521	0.245	5.780	5.540	3.97	0.012	0.30
ACC3	521	0.235	5.830	5.595	2.59	0.014	0.25
ACC4	521	0.245	5.825	5.580	3.43	0.011	0.25
ACC6	991	0.560	6.150	5.590	1.77	0.012	0.14

Table 1: Responses of the blast sensors in PMT-1 implosion test.

4. PMT Implosion Simulations and “blind” NUWC Test Predictions

In an effort to develop a computational tool that can be utilized to optimize the photomultiplier tube arrangement in the LBNE experiment, an elaborate numerical analysis was conducted. The main objectives of this multi-faceted effort were (a) the benchmarking of a physics-based implosion model against data from relevant past studies, (b) the evaluation of the strength of the selected PMT in coordination with other hydrostatic tests and the understanding of an implosion-induced shock-wave, and (c) the prediction of the shock field around the imploding PMT under the LBNE ambient parameters to be simulated in the NUWC tests.

The basis for the numerical models used in addressing the experiments and studies is the Arbitrary Lagrangian Eulerian (ALE) formulation provided by the LS-DYNA [7] explicit code which enables the study of both fluid and solid parts and their interaction under highly non-linear processes such as the PMT implosion. The capabilities of the TrueGrid [8] software were utilized to generate an accurate 3-D description of the various test configurations. The analysis was performed ahead of the experiments, and it was necessary to make certain assumptions regarding the equation of state (EOS), constitutive, and glass fracture relations governing the PMT glass material. Specifically, the properties of float silica glass adopted into the Johnson-Holmquist model [7] were used to describe the PMT glass wall in the implosion simulations.

4.1. Benchmarking of Implosion Tests

Some previous glass sphere implosion experiments conducted at NUWC [6], were used as the benchmark frame for the 3-D ALE computational model being developed for the LBNE PMT implosion studies. Additional benchmark studies were performed addressing the “bubble” collapse/oscillation [5] problem for which analytical and semi-analytical solutions exist and for which the role of the glass is eliminated thus

representing the “limiting” case in terms of generated peak pressures. For both the glass sphere implosion experiments and the bubble collapse problem the numerical model accurately predicted both peak pressures and arrival times thus providing confidence in analyzing the more complex PMT implosion issue.

4.2. Simulation of the NUWC Implosion Test

Following the benchmarking of the numerical processes, a numerical model was developed to analyze the PMT implosion tests within the large pressurized vessel at NUWC facility with a hydrostatic pressure of 0.61 MPa. The implosion of the PMT was initiated with a mechanical device. By taking advantage of the symmetry plane a model consisting of a total of $\sim 2,240,000$ elements representing the PMT glass structure (Lagrangian) and all the fluid volumes (Eulerian) was developed. The PMT was assumed to have base encapsulation to protect the high voltage pins. This part was assumed to remain structurally stable. To ensure that the pressure driver of the implosion is not lost following the fracture of the PMT glass, a large volume of the surrounding water was used along with radiating boundaries at the water volume edge. The implosion analysis consisted of an initialization phase establishing the state of stress in the PMT wall followed by a transient phase capturing the glass damage initiation and the subsequent implosion. The duration of the glass implosion was of primary interest, given the ambient pressure of 0.61 MPa, and the subsequent pressure intensity and spatial attenuation. An analysis time of 8 ms following the PMT fracture initiation was used. Figure 5 depicts the initiation of the shock within the volume of the imploded PMT followed by the outward propagation.

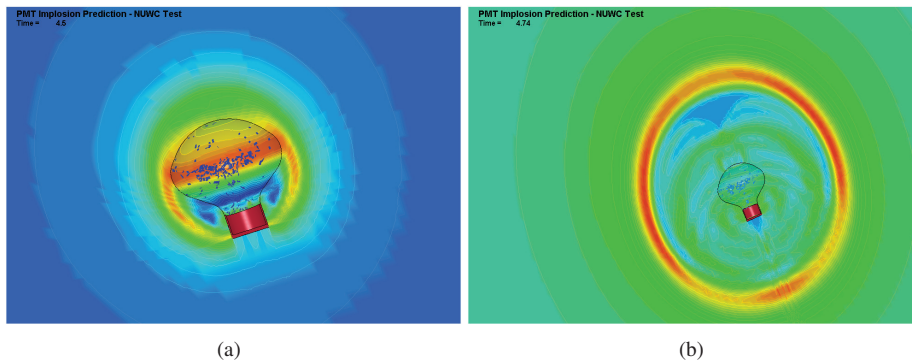


Fig. 5: The pictures show simulation of the pressure in the water as a function of time at 4.6 ms on left and at 4.74 ms on right. The original outline of the imploded PMT is shown in the picture to provide a scale for the pictures. A nearly spherical band of high pressure is seen to propagate from the PMT as it implodes. The color scale for this visualization is arbitrary.

The comparison between the PMT-1 test data and simulation results is shown in Figure 6. Shown are pressures near the mechanical device used to initiate the fracture that is close to the PMT wall (ACC11), and at ~ 0.5 m (ACC1) radial distances from the center of the PMT. The simulated pressure waveform agree with the real test data fairly well. There are some differences between the real tests and the simulation. In the simulation, the pressure readings drop quickly at the beginning of the implosion, while it is smooth for the real data. The duration of implosion for the simulation is always shorter than the actual tests by around 0.5 ms. These differences are most likely related to differences in the properties of the glass. We have used the properties of silica glass in the simulation, since we do not have the fracture properties of the PMT borosilicate glass. Those properties make a difference in the collapse speed of glass. Another main difference between the real tests and the simulation is the peak pressure value. The simulated peak pressure is smaller than the actual test data by about 30%. Since the peak pressure is also strongly correlated with the glass cracking and collapsing, the lack of agreement at this level may also be related to the property of the glass. And the PMT glass cracking asymmetry could cause the asymmetry of the shock wave formation, including the width and the peak pressure of the shock wave. With the limited statistics and uncertainties

of the pmt implosion tests, current simulation describes the PMT implosion process fairly well, even with large uncertainties on the glass properties.

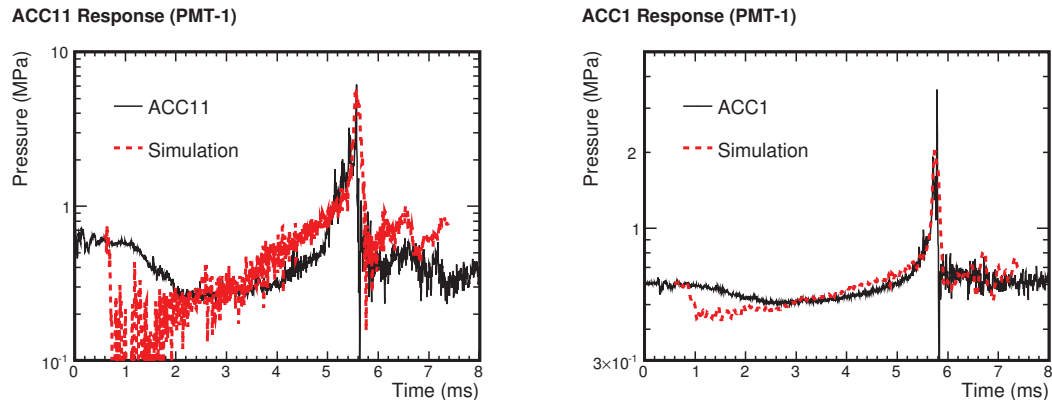


Fig. 6: Comparison between the simulated pressure pulse and the test results at the locations of pressure sensors. The time of the simulation results were adjusted so that the times of the pressure peak match for the sensor closest to the PMT.

5. Conclusions

Two photo-multiplier tube implosion failure tests were performed in a large diameter pressurized water tank to simulate water Cerenkov detector operating condition. Detailed measurements of implosion time, the pressure as a function of time near the PMT, and the intensity of the shock wave, have been recorded and a comparison of the data to modern hydrodynamic simulation is made. The simulation predicts the timescale of the implosion event and the peak pressure in the resulting shock wave. The simulation is found to under-predict the peak pressure and have slightly shorter duration. We attribute these disagreements to the lack of data pertaining to the exact properties of glass. The responses of neighboring PMTs to the shock wave will be studied in the next phase of multiple-PMT implosion tests in the near future. The simulations we have developed could be extrapolated to other PMT assembly geometries and make recommendation on deployment of the photo-multiplier sensors in deep detectors with a focus on mitigation of an implosion chain reaction.

6. Acknowledgment

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References

- [1] Neutrinos and Beyond: New Windows on Nature, Neutrino Facilities Assessment Committee, National Research Council, (2003), ISBN-0-309-087 16-3, Also see "US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years," Report of the Particle Physics Project Prioritization Panel, May 29, 2008, http://science.energy.gov/~media/hep/pdf/files/pdfs/p5_report_06022008.pdf
- [2] V. Barger, *et al.* FERMILAB-0801-AD-E, BNL-77973-2007-IR, May 2007. 109pp. e-Print: arXiv:0705.4396
- [3] M. Diwan, J. Dolph, J. Ling, T. Russo, R. Sharma, K. Sexton, N. Simos and J. Stewart *et al.*, "Underwater implosions of large format photo-multiplier tubes," Nucl. Instrum. Meth. A **670**, 61 (2012).
- [4] Y. Fukuda *et al.*, Nucl. Instrum. Meth. A **501**, 418 (2003).
- [5] Lord Rayleigh, "On the pressure developed in a liquid during the collapse of a spherical cavity", Philos. Mag. **34**, 94-98 (1917)
- [6] S. Turner, Underwater implosion of glass sphere, J. Acoust. Soc. Am., 121 (2), 2007
- [7] LS-DYNA, LSTC Software, Livermore, CA.
- [8] TrueGrid, XYZ Software, Livermore, CA.